CONFERENCE PROCEEDINGS

Assessment of Potential Well Leakage in the Weyburn Site Using a Stochastic Approach

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Abstract

This paper details the modeling approach and results of assessing potential well leakage of CO_2 injected into oil fields. The challenge of the assessment includes the large number of wells, spatial variability (reservoir properties and CO_2 distribution), upscaling, and uncertainty in the long-term integrity of the abandoned well cement plug. The model to be presented in this paper addresses spatial variability by utilizing a probabilistic approach to integrate field data with the results obtained from geological characterization, reservoir simulation, and the natural-barrier CO_2 containment assessment. The model includes multiphase and multi-component flow and transport governed by the equations-of-states. Sensitivity analyses were conducted to investigate the impact of cement transport properties. A range of CO_2 leakage rate and cumulative leakage for up to 5000 yrs were obtained based on assumptions biased towards overestimating leakage. Potential consequences to the local environment were then assessed using existing regulations.

1. Introduction

Using anthropogenic CO_2 to enhance secondary or tertiary oil recovery (EOR) is a promising option for CO_2 geological sequestration. As oil is produced, injected CO_2 is expected to stay indefinitely in the vacant pore space. Such operations are currently carried out worldwide, an example of which is the Weyburn field located in Saskatchewan, Canada.

In July 2000, a 4-year research project to study geological sequestration and storage of CO_2 was launched, known as the International Energy Agency (IEA) Weyburn CO_2 Monitoring and Storage Project. CO_2 from the North Dakota Gasification plant is transported and injected into an approximately 1450-m deep oil reservoir for EOR. The operator, EnCana Resources of Calgary, Alberta, has designed a total of 75 patterns for this operation that will last for approximately 34 years. Phase I of the CO_2 sequestration research has been sponsored by a number of governments and industrial sponsors from North America, Europe and Japan, including EnCana, Natural Resources Canada (NRCan) and the U.S. Department of Energy (DOE).

Numerical simulation of the detailed geosphere containment assessment model (Zhou et al., 2004) demonstrated that the site is able to contain all of the injected CO_2 for up to 5000 yrs. Specifically, 26% of the initial CO_2 inventory (i.e., total CO2-in-place at the end of EOR) is removed to the aquifers below the reservoir by formation water or ends up in the Midale formation (the same geological formation as the reservoir) outside the EOR area. No CO_2 enters any potable aquifers over the 5000-year period. While this result enhances confidence regarding the performance of the geological barriers, a remaining concern is the potential risk of leakage of >70% of initial CO_2 trapped in the reservoir through abandoned wells.

Abandoned wells in an oil field are sealed according to local government regulations. While regulations vary from place to place, the common practice involves plugging the wellbore with cement material specially designed for the isolation purposes (Fig.1). Like any man-made materials, cement is expected to degrade over time under various subsurface conditions. Although observations suggest that cement plugs are able to perform as expected for up to several decades, uncertainty exists that the material can maintain its isolation integrity for several thousand years, the timeframe in which CO_2 is expected to remain underground. Potential leakage through degraded cement plugs is, hence, the primary concern of CO_2 sequestration in oil and gas fields because of the large number of existing and future wells.

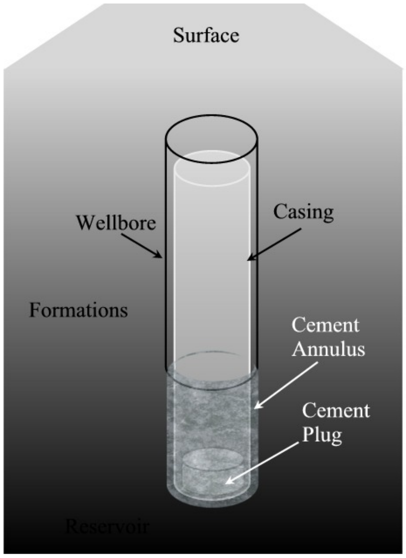

Fig.1. Illustration of sealing of an abandoned well.

Challenges in quantitatively predicting the potential long-term leakage include (1) the number of wells (currently >800 wells already exist in the Weyburn EOR area and more likely will be drilled), (2) heterogeneous reservoir properties, (3) variable fluid saturations and species (hydrocarbons and CO_2) concentrations, and (4) uncertainty in long-term cement degradation rate. Obviously, one cannot simulate the evolution of all the wells in the whole reservoir in one numerical model.

In this case, a probabilistic assessment approach should be adopted, which propagates parameter uncertainty and variability through a simplified model. In this paper, we will demonstrate the approach to assess potential leakage and environmental impact of abandoned wells using the example of the Weyburn field. The emphasis of the present study is on spatial heterogeneity and variability combined with conservative cement transport parameter values (1) in order to study the effect of spatial heterogeneity and variability, and (2) because insufficient information was available during the Weyburn Project Phase I to quantify cement degradation rate and resultant transport properties. Nevertheless, the approach can be easily extended to include cement transport parameter uncertainty when information becomes available.

2. The "Unit Cell" Model

The probabilistic assessment model used in the present study is the "Unit Cell" model that focuses on a single well as shown in Fig.2. This is a 2D (*r*-*z*) numerical model with a spatial discretization that can incorporate the well dimension. The model includes the important components of a well system: cement plug (~8 m long), cement annulus, metal casing, open borehole above the plug, and a portion of reservoir. Leakage is defined as CO_2 in the reservoir reaching the water-filled open borehole immediately above the cement plug. The following assumptions further simplify the model:

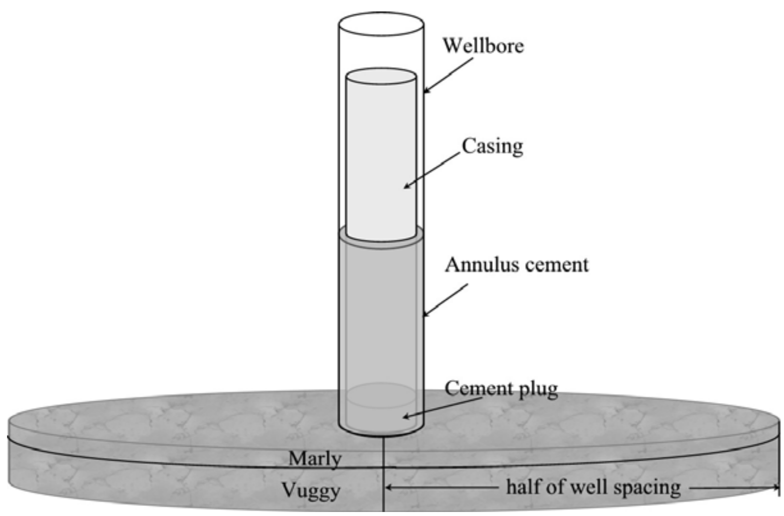

Fig.2. Illustration of the "Unit Cell" model. "Marly" and "Vuggy" is the upper and lower reservoir formation (Midale Beds), respectively.

(1) The compositional model is the same as the geosphere assessment model (Zhou et al., 2004), i.e., the modified Peng-Robinson equations-of-states governing three phases (water, oil, and gas) and seven components (six hydrocarbons and CO_2) with CO_2 partitioning in all three phases. An

empirical relation for CO_2 solubility by Chang et al. (1996) was employed. The temperature of the system is constant at 64 C.

(2) Permeability of cement plug and annulus in contact with aquitards changes from 0.001 mD initially to 1 mD at 100 yrs after the end of EOR when the reservoir pressure transient is nearly finished and buoyancy force becomes important to fluid flow. This assumption is based on the scoping analysis by Chalaturnyk et al. (2003) that predicted cement degradation corresponding to a change in permeability from 0.001 mD to 1 mD occurring after 1000 yrs. In this assumption, the scoping analysis result was used with a bias towards overestimating leakage.

(3) Currently, there is insufficient information on capillary pressure for degraded cement material. In this study, the capillary pressure for degraded cement is obtained by modifying the capillary pressure for fresh cement (Yu et al. 1995) and the relationship between permeability k [m^2] and mean pore size r [r] (Scheidegger, 1974):

$$k \propto r^2 \qquad p_c \propto \frac{1}{r}$$

where p_c is capillary pressure [Pa]. Therefore, given a permeability change, one can estimate the change in capillary pressure using the above equations. Fig.3 shows the capillary pressure curves for fresh and aged cement materials with three orders of magnitude of permeability increase.

(4) The metal casing corrodes and reduces to a gel-like corrosion product between the annulus and the plug. This material is assumed to have the same property as the cement.

(5) Cement is initially water-saturated at hydrostatic pressure.

(6) The diameter of the reservoir in each "Unit Cell" is equal to the mean well spacing (240 m) that is derived from UTM coordinates of existing wells. The initial conditions in the reservoir are homogeneous and defined by the geosphere containment assessment model parameters and the results at 100 yrs after the end of EOR through stochastic method. Leakage via wells is assumed to be the only way for CO_2 in the reservoir to escape confinement.

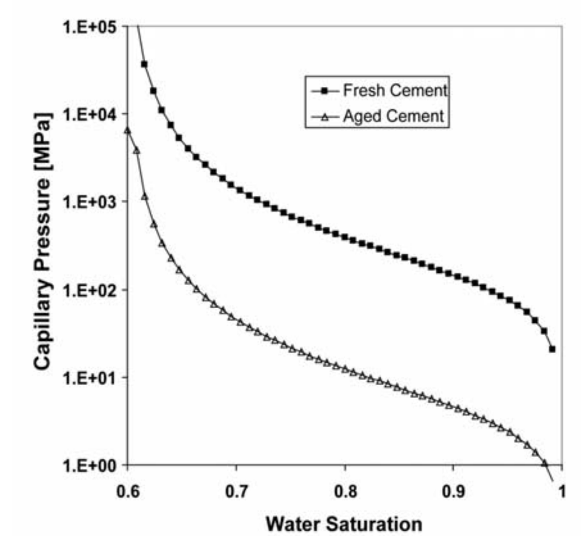

Fig.3. Capillary pressure vs. water saturation for fresh and aged cement materials.

(7) In addition to pressure-gradient and buoyancy driven flow, mass transfer of CO_2 can take place by molecular diffusion. Diffusion coefficients were taken from Grogan et al. (1986).

(8) Zero CO_2 concentrations are assumed in the open borehole where CO_2 would form gas bubbles and ascend rapidly.

The model is simulated using an industry-standard reservoir simulator E300 developed by Schlumberger/GeoQuest.

3. Treatment of Reservoir Spatial Heterogeneity and Variability

To address spatial heterogeneity and variability, the reservoir properties and initial conditions (permeability, pressure, saturations, concentrations, etc) in each "Unit Cell" calculation are taken from the model parameters and the 100-yr result for a grid in the EOR area of the geosphere assessment model. Fig.4 shows the reservoir formation and the EOR area in the geosphere assessment model. It can be seen from Fig.4 that after the completion of EOR, CO_2 moves spontaneously and "freely" within the geosphere under, primarily, the EOR residual pressure gradient.

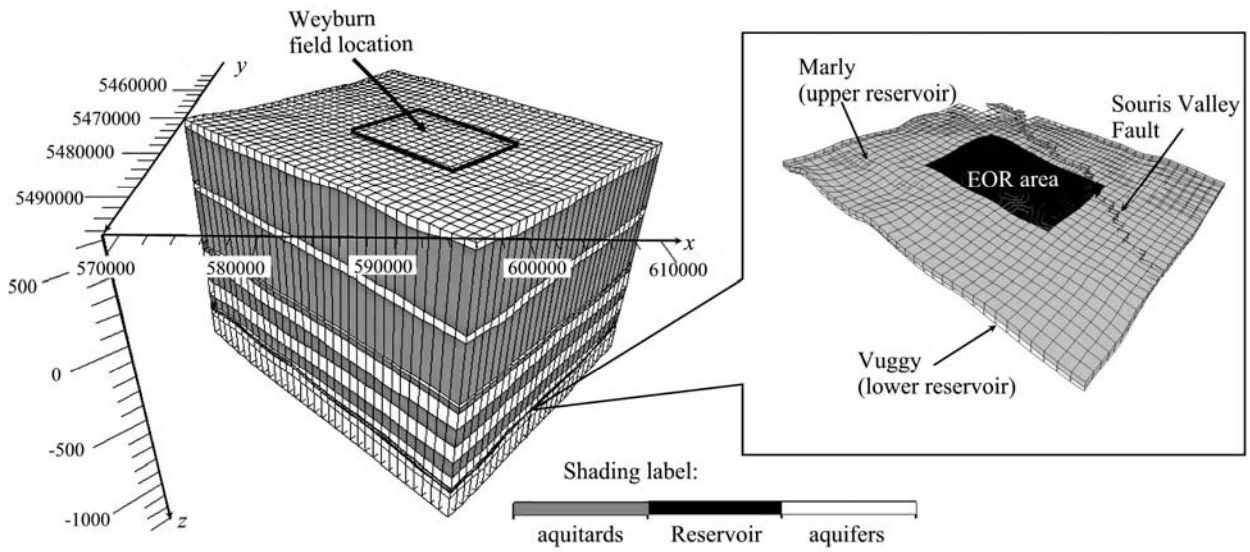

Fig.4. The geosphere containment assessment model and the reservoir (Midale) formation where the EOR area is located.

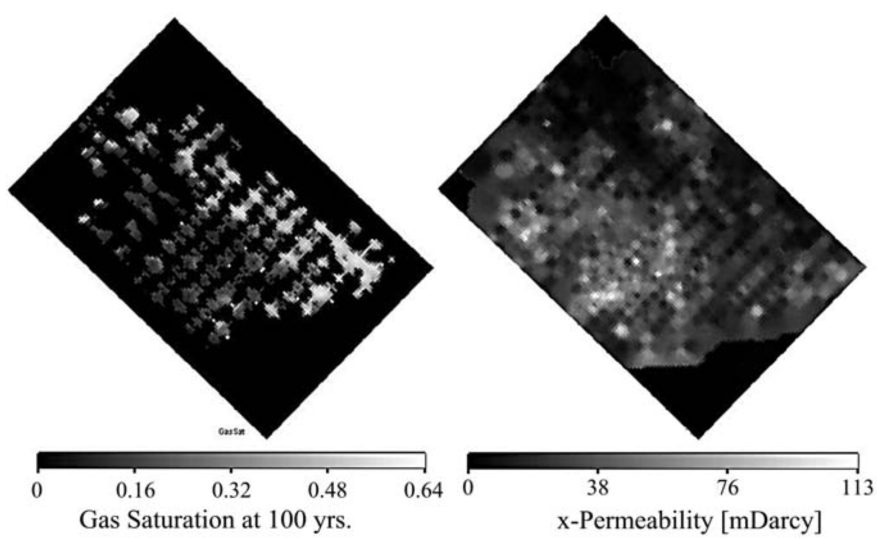

Fig.5. Distributions of gas saturation at 100 yrs after the end of EOR and *x*-permeability values in Marly, the upper reservoir formation.

Fig.5 shows the distribution of gas saturation in the upper reservoir at 100 yrs after the end of EOR, as an example of varying fluid thermodynamic states in the reservoir. Note that the gas is primarily CO_2 at supercritical thermodynamic states.

Fig. 5 also shows the distribution of *x*-permeability values as an example of heterogeneous reservoir property. Obviously, in each grid of the EOR area shown in Fig.4, there are certain values of permeability, porosity, saturations, and concentrations for both upper and lower reservoir formations. This means that for the studied system, the spatial heterogeneity and variability can be regarded as a property rather than an uncertainty. To maintain the integrity of this information, as well as the thermodynamic constraints on fluid saturations and concentrations dictated by the equations-of-states, the approach to spatial variability should be to keep together the important parameters found in a reservoir grid (including both upper and lower formations) in the geosphere model.

To achieve this, a group of the reservoir grids out of total 12,150 grids were sampled with biases towards (1) existing well locations (see Fig.6), (2) high permeability values (where future wells may be drilled), and (3) high CO_2 inventory at 100 yrs. As a robust assessment philosophy, this biased sampling, combined with conservative assumptions for the "Unit Cell" model, will predict an overestimated leakage. Fig.7 shows the CO_2 inventory comparison for the total "population" of the grids and the sampled grids (287 grids were selected). It can be seen that the sampled grids over-represent the population with high CO_2 inventory.

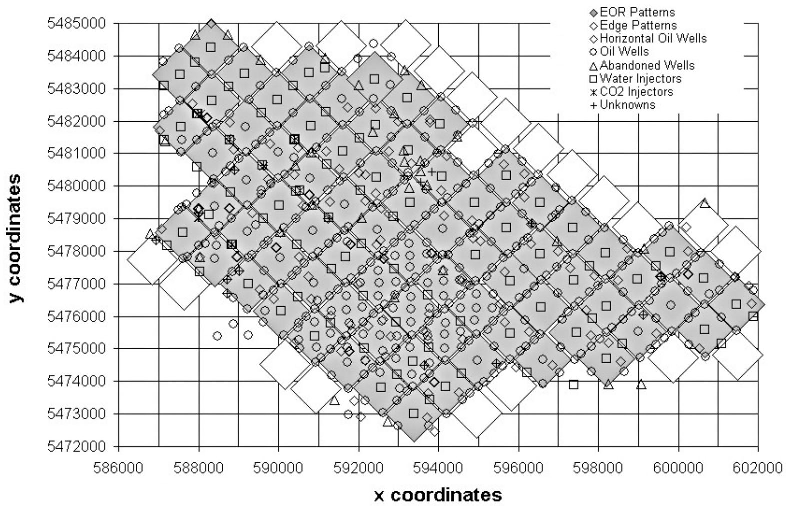

Fig.6. Existing wells in the EOR area and vicinity.

4. Results

The "Unit Cell" model calculated was conducted for 287 times, with each initial reservoir parameters defined by the 100-yr results in one of the selected grids. The simulation is from 100 yrs to 5000 yrs after the end of EOR. These calculations generated 287 histories of leakage rates and cumulative leakages. The statistical leakage rate histories are plotted in Fig. 8 along with leakage rate vs. time from selected runs. Note that in Fig. 8, the 5% result is out of scale. The statistical result shows a large variation in leakage behavior. For all the leaking wells, the leakage rate increases with time initially, but at different rates. Some reach a peak at early times while others peak at later times or never reach a peak within 5000 yrs. The peak leakage rates also vary greatly: from zero (no leakage) to a *maximum* of 0.012 kg/day.

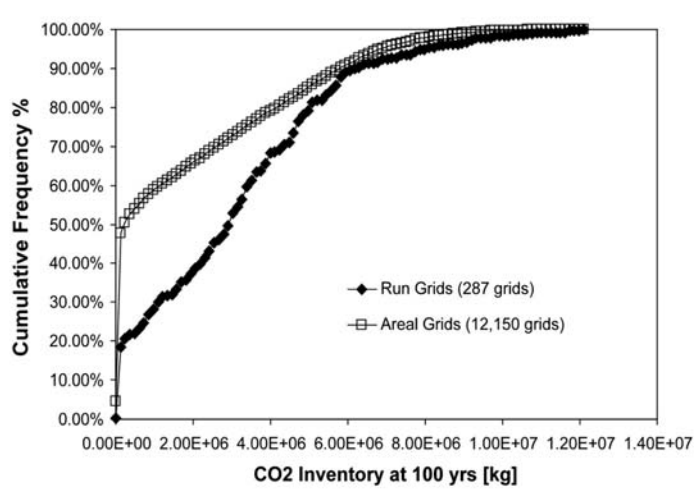

Fig.7. Comparison of CO_2 inventory at 100 yrs after the end of EOR between the total number of grids in the EOR area ("Areal Grids") and the selected "Run Grids."

Results were analyzed in an attempt to identify correlations between the maximum leakage rates and reservoir parameters, including horizontal and vertical permeability, gas saturation, CO_2 concentrations, etc. in both the Midale Marly and Vuggy layers. Fig. 9 shows the scatter plot of the maximum leakage rates from the 287 runs against the total CO_2 mass in water in the corresponding 287 grids. The total CO_2 aqueous mass is the sum of the CO_2 mass in the water fraction of the Midale Marly and Vuggy layers, calculated using the corresponding water saturation, CO_2 aqueous concentration, density, and pore volume of each grid. It can be seen that in general, the maximum leakage rate is associated with high CO_2 aqueous concentration, consistent with the observed cement property being restrictive to non-aqueous phases. Additional analysis has shown that the high leakage rate is generally associated with high permeability values, high gas saturation, and high CO_2 concentrations in all three phases, while low leakage rate is associated with low permeability, low (or zero) gas saturation, and low CO_2 concentrations. The number of grids with such an extreme combination of key parameters, however, is small. In most grids, these parameters are combined rather chaotically.

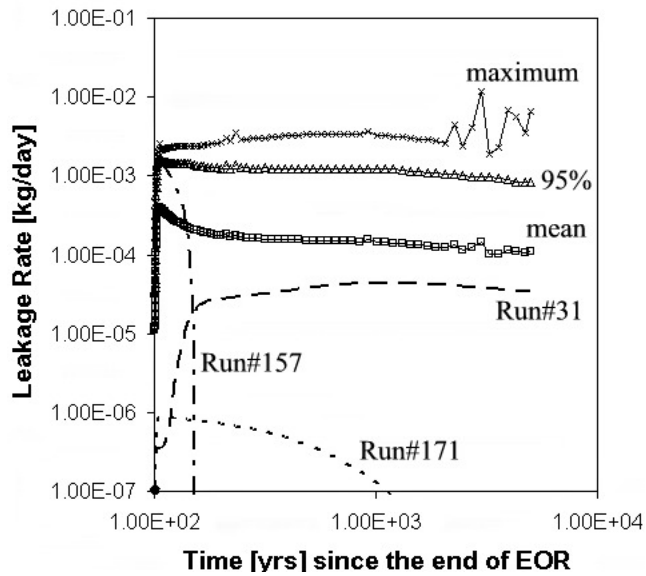

Fig. 8. Statistical results of CO_2 leakage rates as a function of time and the results of a few selected runs.

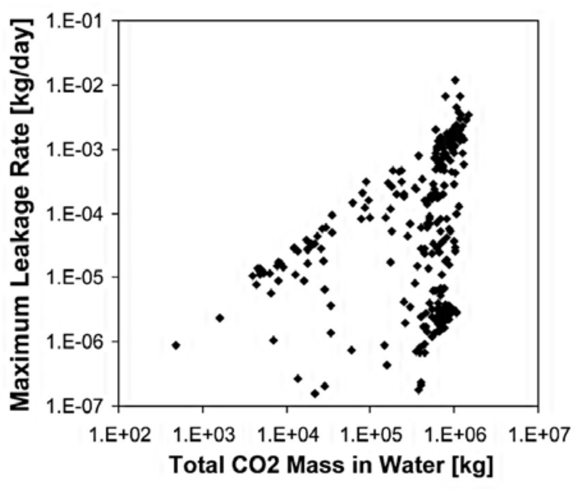

Fig. 9. Scatter plot of the maximum CO_2 leakage rates and CO_2-in-water.

Variability in well leakage is also demonstrated in the cumulative leakage shown in Fig. 10 as the 5%, mean, 95%, and maximum cumulative leakage as a function of time.

In general, the stochastic nature of reservoir conditions dictates stochastic behavior of leakage through abandoned wells across the EOR area. However, when the cement permeability is low (≤ 1 mD), the ultimate control of leakage lies in the cement permeability. When the cement permeability is higher (e.g., >10 mD), reservoir properties dominate leakage process, in which case, the reservoir variability plays even a greater role. To confirm this, a few "Unit Cell" runs were carried out using an increased cement permeability (10 mD), and the results indicated an increase in the maximum leakage rates ranging two- to ten-fold – not all well's leakage increases in proportion to cement permeability.

Combining the *maximum* CO_2 cumulative leakage through a wellbore (4250 kg) at 5000 yrs (Fig. 10), with an estimated 1,000 wells over the EOR area (currently ~800 wells), yields a total cumulative leakage of CO_2 of ~0.004 MT. This total amount represents ~0.02% of the total CO_2 inventory (21 MT) at the end of EOR. This value is a highly-conservative upper estimate, however, as it assumes that all wells generate the maximum leakage by 5000 yrs. Thus, a more representative value is the *mean* cumulative leakage, corresponding to less than 0.001% of the CO_2 inventory at the end of EOR.

5. Potential Environmental Impacts

To provide some perspective on wellbore leakage rates, reference is made to scoping calculations conducted to determine the limiting CO_2 flux from the geosphere based on specific (local) environmental impacts (Stenhouse et al., 2004). Two specific impacts were assessed in (Stenhouse et al., 2004): (i) influx of CO_2 from a point source (wellbore) into a dwelling through cracks in the foundations of the home, and (ii) influx of CO_2 from a point source into a potable groundwater supply, with resultant mobilization of toxic trace elements.

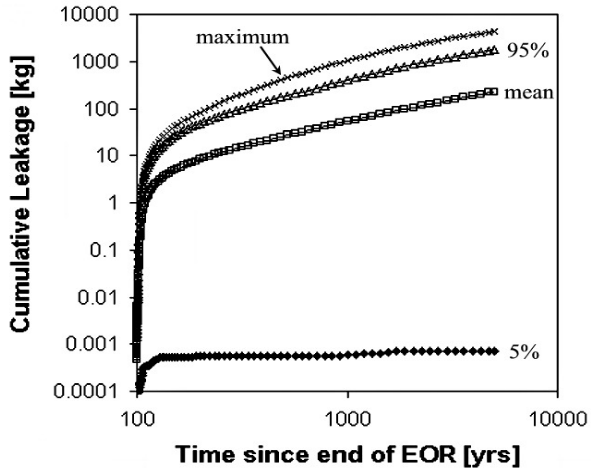

Fig.10. Statistical results of cumulative leakages of CO_2 through abandoned wells.

For the former case, a limiting indoor air CO_2 concentration of 0.35% (Health Canada, 1989) yields a limiting leakage rate from a wellbore of 5.4 kg CO_2 per day, more than two orders of magnitude greater than the predicted maximum leakage rate (0.012 kg/day). For the latter case, CO_2 leakage to a potable aquifer proved more restrictive, yielding a limiting CO_2 leakage rate (based on the possible release of lead to the water) of similar magnitude to the mean cumulative leakage described above. More detailed treatments of these environmental impacts are recommended before making a definitive statement on an acceptable CO_2 leakage rate to the biosphere. For example, results elsewhere (Oldenburg and Unger 2003) indicate a possible CO_2 build-up in the vadose zone, which could impact the resultant CO_2 concentration in indoor air.

6. Conclusions

The study indicates that the spatial variability in reservoir properties and parameters plays a key role in potential leakage via degraded well cement for a given permeability value of degraded cement. For the specific case relevant to the Weyburn Project, the overestimated leakage rates and cumulative leakages indicate that the potential leakage via abandoned wells will not likely compromise the goal of CO_2 sequestration and the global environment.

With respect to the local environment, scoping calculations demonstrate that the maximum leakage rate does not impose any hazard to indoor air quality. With respect to potential potable aquifer impacts, the mean CO_2 leakage rate, according to the scoping calculation, could generate the release of a toxic metal (lead) into a potable aquifer at a concentration comparable with the current action level.

Note that the study and results presented here are based on a series of conservative assumptions, which overestimated leakage rates and cumulative leakage at 5000 yrs. The model can be improved in many aspects. Firstly, for example, the model should incorporate uncertainty in cement degradation rate, if such information becomes available, instead of assuming that all wells degrade at the same rate even though the rate selected was higher than the preliminary Phase I prediction. Secondly, the model should incorporate variability in well spacing that determines the total amount of CO_2 available to leakage. Thirdly, the model should incorporate CO_2 removal by formation water flow and its uncertainty within and below the reservoir. All these improvements will help reduce conservatism in the current model and thus generate more realistic results.

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